Developing a Robust, Interoperable GNSS Space Service Volume (SSV) for the Global Space User Community

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BIOGRAPHIES

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Bryan Welch is an Electronics Engineer in the Advanced High Frequency Branch (Code LCF) at NASA Glenn Research Center (GRC) in Cleveland, Ohio. Mr. Welch contributes to several projects in the fields of communication and navigation system analysis. He currently supports the GRC SCENIC Project as the Lead Communications Engineer and the GRC Cognitive Communications Project as the RF/Communications Lead of the SCaN Testbed payload, as well as having previously supported the GRC GPS/PNT Project as its Technical Lead and working with international partners of the ICG WG-B in its technical analysis development. Mr. Welch received a Bachelor of Electrical Engineering in 2003 and Master of Science in Electrical Engineering in 2006, both from Cleveland State University, and is currently finalizing his Dissertation Research activities in support of his Doctorate of Engineering degree. Mr. Welch joined NASA in 2002.

Werner Enderle is the head of the Navigation Support Office at ESA's European Space Operations Center in Darmstadt, Germany. Previously, he worked at the European GNSS Authority (GSA) as the Head of System Evolutions. He also worked for the European Commission, in charge of the procurement for the Galileo Ground Control Segment. He holds a doctoral degree in aerospace engineering from the Technical University of Berlin, Germany.

ABSTRACT

For over two decades, researchers, space users, Global Navigation Satellite System (GNSS) service providers, and international policy makers have been working diligently to expand the space-borne use of the Global Positioning System (GPS) and, most recently, to employ the full complement of GNSS constellations to increase spacecraft navigation performance. Space-borne Positioning, Navigation, and Timing (PNT) applications employing GNSS are now ubiquitous in Low Earth Orbit (LEO). GNSS use in space is quickly expanding into the Space Service Volume (SSV), the signal environment in the volume surrounding the Earth that enables real-time PNT measurements from GNSS systems at altitudes of 3000 km and above. To

support the current missions and planned future missions within the SSV, initiatives are being conducted in the United States and internationally to ensure that GNSS signals are available, robust, and yield precise navigation performance. These initiatives include the Interagency Forum for Operational Requirements (IFOR) effort in the United States, to support GPS SSV signal robustness through future design changes, and the United Nations-sponsored International Committee on GNSS (ICG), to coordinate SSV development across all international GNSS constellations and regional augmentations. The results of these efforts have already proven fruitful, enabling new missions through radically improved navigation and timing performance, ensuring quick recovery from trajectory maneuvers, improving space vehicle autonomy and making GNSS signals more resilient from potential disruptions. Missions in the SSV are operational now and have demonstrated outstanding PNT performance characteristics; much better than what was envisioned less than a decade ago. The recent launch of the first in a series of US weather satellites will employ the use of GNSS in the SSV to substantially improve weather prediction and public-safety situational awareness of fast moving events, including hurricanes, flash floods, severe storms, tornados and wildfires. Thus, the benefits of the GNSS expansion and use into the SSV are tremendous, resulting in orders of magnitude return in investment to national governments and extraordinary societal benefits, including lives saved and critical infrastructure and property protected. However, this outstanding success is tempered by dual challenges: that for GPS, the current SSV specifications do not adequately protect SSV future use; and that for GNSS, the capabilities that are currently available are not protected in the future by specifications.

INTRODUCTION

GPS and all other GNSS constellations consist of a core volume of satellites, primarily in Medium Earth Orbit (MEO), transmitting one-way radio signals that are used to calculate three-dimensional position and time in the terrestrial and near-Earth domain. To achieve this, traditionally at least four GNSS satellites are needed to be within line-of-sight at any given time to enable on-board real-time autonomous navigation through the formation of a point solution. Continuous availability of at least four signals has become a standard expectation for GNSS users within the Terrestrial Service Volume (TSV), the regime from the surface of the Earth to 3,000 kilometers altitude, including much of low Earth orbit (LEO). Space users in the TSV have unique technical challenges as compared terrestrial-based GNSS users (land, sea and air vehicles) [1], but over the past two decades, many of these technical challenges have been overcome [2]. This has been accomplished through technology investments, spaceborne receiver developments, and on-orbit flight characterization tests. Beyond the TSV, additional challenges arise for space users interested in employing GNSS signals. The number of available GNSS signals decreases and, because of poor geometry and blockage of main beam reception by the Earth, four GNSS signals are rarely available from any single constellation to enable formation of a point solution. Compounding these issues are the limitations imposed by GNSS service providers either intentionally, in an attempt to maximize Earth signal coverage, or unintentionally, through inadequate or nonexistent specifications. This region is known as the Space Service Volume (SSV), and is the subject of several ongoing initiatives to enhance and protect its capabilities.

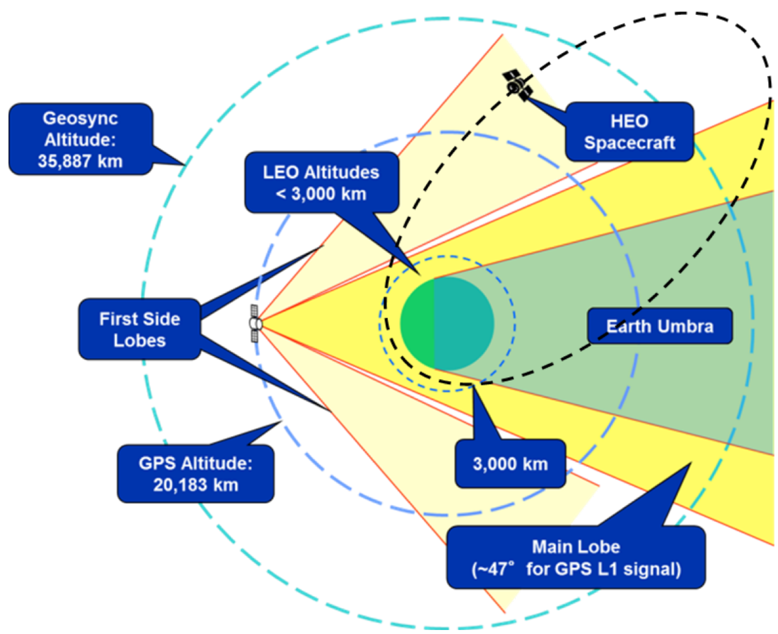

Figure 1: Geometric View of GNSS Signal Use in Space

A better understanding of some of the challenges of using GNSS in the SSV can be gleaned by studying Figure 1, a two-dimensional geometrical depiction of GNSS reception in space. In this figure, the three dashed circles represent (from the inside out): 1) the 3,000 km upper limit of the Terrestrial Service Volume, which also represents the lower limit of the Space Service Volume, 2) the GPS orbit at 20,000 km, and 3) the 36,000 km geosynchronous orbit altitude, which also represents the upper limit of the Space Service Volume. Figure 1 depicts a typical GNSS satellite with its main lobe signal depicted in dark yellow and its first side lobe signal shown in light yellow. On this graphic is a representative spacecraft in an eccentric high Earth orbit that spans low-altitude and high-altitude regimes. As is evident from the geometry, spacecraft within the high Earth orbit and geostationary orbit regime of the SSV rely predominantly on signals that pass over the limb of the Earth. As shown in Figure 1, the geometric availability of main lobe signals is relatively small when compared to the full width of the main lobe signal. Using GPS as an example, at geostationary altitude, four simultaneous main lobe signals may only be available 1% of the time, and outages may exceed 100 min. This leads many users to consider using the full aggregate signal, including both main and side lobes. Compared to missions in low Earth orbit, users in the SSV must acquire and track signals that have significantly longer signal paths, and thus lower received power levels. Also, these sidelobe signals are predominantly lower-power than their main lobe counterparts. But, even considering these constraints, signal availability can be increased dramatically, with nearly continuous availability of 4 or more simultaneous signals, through employment of the aggregate signal. Specially-designed high-altitude GNSS receivers that can acquire and track very weak GNSS signals are used to overcome these factors and increase availability even further. Use of the side lobe signals also improves navigation accuracy due to improved dilution of precision (DOP), through improved signal geometry.

If high-altitude missions were restricted to using only the main lobe signal and only one GNSS constellation, there would be significant periods of time when less than 4 signals with sufficient signal strength could be employed, and there would be significant intervals during which there would be no GNSS signals available to support PNT sensing. Modern on-board navigation filters, coupled with trajectory estimation techniques, are used to process individual measurements when less than 4 signals are available, and to "flywheel" through signal outages. However, these on-board tools do not support rapid navigation solution recovery, such as after a maneuver, when GNSS signals are absent. Thus, ensuring continuous availability of at least 1 signal in view for spacecraft in the SSV is a key performance parameter to ensure robust PNT sensing for space vehicles. There are several architectural alternatives to achieve this. However, the most cost effective, robust, and resilient approach is to employ the aggregate signals (main and side lobes) of one or more GNSS constellations. Currently there are several operational missions employing GPS in the SSV, and most of them take advantage of aggregate signal reception to boost their navigation and timing performance. Encouraging this usage further requires two simultaneous initiatives: updating the single-constellation GPS SSV specification to better reflect the true capabilities of its full aggregate signal, and developing an interoperable multi-GNSS SSV, preferably backed by its own set of specifications.

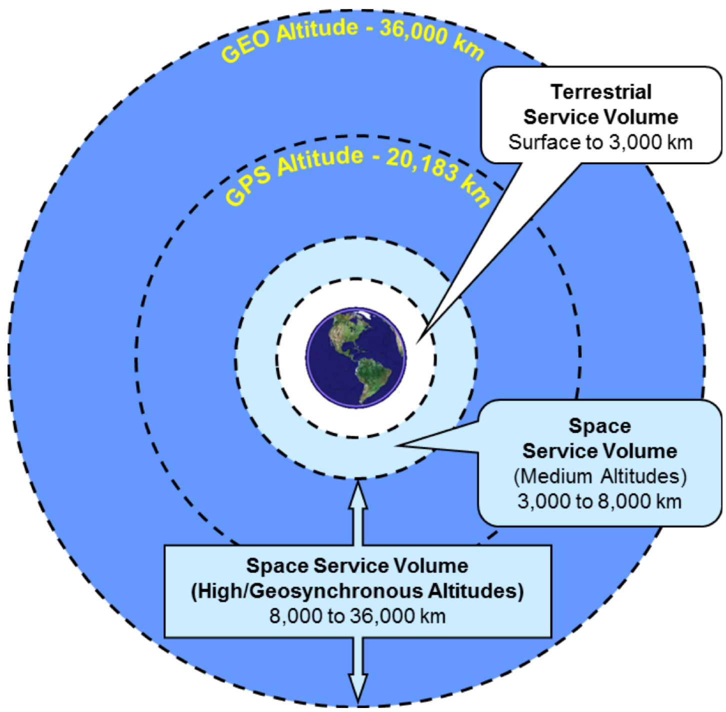

Figure 2: GPS Terrestrial Service Volume and Space Service Volume

SPACE SERVICE VOLUME HISTORY AND DESCRIPTION

To date, the only GNSS constellation with a defined SSV specification is GPS [3]. Originally GPS minimum performance was specified with a beamwidth of 14.3 degrees, just 0.5 degrees over the limb of the Earth, though the GPS main lobe signal itself was much wider. While the actual main lobe signal spillover adequately supported LEO space users, on-orbit performance of the main lobe signal in space was not robust as it varied as the antenna gain pattern varied from block-build to block-build (e.g. Block IIR to Block IIR-M). This impacted both signal power and signal availability for LEO space users and for spacecraft in the more challenging Space Service Volume. To shore up this concern for space users in LEO, HEO and GEO, a major SSV specification initiative was completed in the 2003-2006 timeframe to support the development of GPS Block III, Satellite

Vehicles (SV) 1–10. This specification included definitions of the TSV, the SSV, and key SSV specification parameters that enable mission designers to predict PNT performance for their spacecraft through analysis. The GPS SSV specification and how it was derived is described in detail in Reference 3, and is summarized here.

TSV & SSV Definitions

Requirements for GPS performance in space have been allocated to two service volumes, as shown in Figure 2. The TSV, which includes all terrestrial and space GPS users extending to an altitude of 3,000 km, and the SSV, which extends from 3,000 km to 36,000 km, or approximately the geostationary altitude.

Terrestrial Service Volume (TSV): The TSV can be viewed as an enclosed sphere that extends from the surface of the Earth to 3,000 km altitude. Similar to terrestrial users, space users in the TSV enjoy uniform received power levels and have fully overlapping coverage from the main beams of the GPS satellites, providing full coverage with 4 signals in view and enabling instantaneous navigation solutions.

Space Service Volume (SSV): The SSV can be viewed as an enclosed sphere extending from 3,000 km altitude to 36,000 km, or approximately the geostationary altitude. To accommodate the differing needs of users operating in the SSV, the SSV is subdivided into two regimes: (1) the medium Earth orbit (MEO) SSV, from 3,000 km to 8,000 km, and (2) the high Earth orbit/geostationary Earth orbit (HEO/GEO) SSV, from 8,000 km to 36,000 km.

Defining distinct regions of space enables the accurate capture of varying levels of performance as a function of altitude. The TSV defines the existing terrestrial requirements for GPS performance to apply up to an altitude of 3,000 km. The MEO SSV is a region of space where four GPS signals will still typically be available simultaneously, and one meter orbit accuracies are feasible. Within the HEO/GEO SSV, nearly all GPS signals emanate from GPS satellites over the limb of the Earth; users may experience periods when no GPS satellites are available; and received power levels will be lower than the TSV or MEO SSV. Each service volume (and its subdivisions) cover a range of altitudes, with GPS performance degrading with increasing altitude. The SSV requirements must generally be met at the worst-case location within the SSV, which is typically the highest altitude within that region.

Since SSV users typically cannot rely on the conventional instantaneous GPS position solutions, performance requirements are set by specifying three parameters: (1) pseudorange accuracy, (2) received power, and (3) signal availability.

Pseudorange accuracy: Pseudorange accuracy is an error bound on the GPS range measurement and is a function of the accuracy of the GPS orbit and clock solutions generated by the Control Segment, the age of solution (how long since the last GPS broadcast ephemeris upload from the Control Segment), as well as uncertainty in physical and modeling parameters related to the GPS satellites. One physical parameter contributing to pseudorange accuracy is the uncertainty in the electrical phase center of the transmitter antenna. The antenna phase center is not perfectly co-located with the center of mass of the spacecraft, and the precise location varies between different GPS satellites. Moreover, the apparent phase center location varies as a function of the user's geometry with respect to the GPS satellite. These variations contribute to the observed accuracy as well as the group delay differential between the different signals transmitted from the GPS satellites. For GPS III SV 1–10, SSV pseudorange accuracy shall be less than or equal to 0.8 m (rms), with a goal of less than or equal to 0.2 m (rms).

Received power: For GPS III SV 1–10, the specified minimum received power within the SSV (i.e. at GEO altitude) for each signal, measured off-nadir at either 23.5 degrees (L1) or 26 degrees (L2 & L5), is shown in Table 1.

Signal	SSV Min. Received Power (dBW)	Reference off-nadir angle (deg)
L1 C/A	-184.0	23.5
L1 P(Y)	-187.0	23.5
L1C	-182.5	23.5
L1 M	-183.5	23.5
L2C	-183.0	26
L2 P(Y)	-186.0	26
L2M	-182.5	26
L5 (I/Q)	-182.0	26

Table 1: Minimum Received Power

Signal Availability: The major requirements driver for spacecraft in the MEO SSV is to maximize the availability of GPS signals, with a goal of four satellites always in view (100% availability). In the HEO/GEO SSV, because of the prevalent use of on-board filters, the goal is the availability of at least one GPS signal all the time. This ensures precise on-board timing at all times for users within the HEO/GEO SSV, reducing the need for expensive on-board clocks. It also ensures that the vehicle's navigation performance is not degraded during stationkeeping maneuvers, after which a continuously-available GPS signal enables users to detect and quickly correct the navigation estimate of the vehicle orbit. For GPS III SV 1–10, the signal availability specification is depicted in Table 2. Note that only the L2 and L5 signals in the MEO SSV meet the ideal goal of full availability.

Assuming a nominal, optimized GPS constellation and no GPS spacecraft failures, signal availability at 95% of the areas at a specific altitude within the specified SSV are planned as:

	MEO SSV		HEO/GEO SSV	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	≥ 80% [1]	≥ 1%
L2, L5	100%	100%	≥ 92% [2]	≥ 6.5%

1. With less than 108 minutes of continuous outage time.
2. With less than 84 minutes of continuous outage time.

Table 2: Minimum Availability Requirement

The GPS III SV 1–10 specification resulted in a more robust capability for space users, particularly LEO users. However, it only specified the main lobe signal and did not meet the major requirements drivers described above. While missions at and beyond GEO have consistently tracked more than 4 GPS aggregate signals 100% of the time, the current specification has left users in the SSV who use the full aggregate signal vulnerable to future GPS design changes. This presents a risk to project managers who wish to employ GNSS for precise navigation and timing on their vehicles. They cannot be assured that future GPS signals (e.g. GPS III SV 11 and beyond) will support the level of performance needed to meet their mission requirements in the long term. This becomes especially concerning for those series of missions in the SSV that continue operations for decades and for those missions that rely on the GNSS signals to quickly recover from maneuvers.

NASA-LED INITIATIVE TO UPDATE GPS SSV REQUIREMENTS

When the GPS SSV specification was adopted in 2006, the space community did not have a full understanding of the current capabilities and limitations of GPS signals in the SSV. For example, while a comprehensive characterization of signal availability was performed through the AMSAT-OSCAR-40 flight experiment [4], aggregate signal navigation accuracy and on-orbit navigation performance in the SSV would not be known until 2015, when the first NASA operational mission of GPS in the SSV—the Magnetospheric Multiscale Spacecraft (MMS)—was launched and started science operations. [5, 6]. Because of this limited knowledge at the time, the 2006 GPS SSV specification only addresses the use of the main lobe signal.

In mid-2015, shortly after the superb SSV navigation performance of MMS was discerned and the critically-important role that GPS at GEO planned to play in GOES-R weather satellite performance was fully understood, NASA began an initiative to update the SSV specification for the next GPS procurement, GPS III SV11+. NASA employed the civil GPS requirements process through US government civil-military engagement via the Interagency Forum for Operational Requirements (IFOR) team. The IFOR is jointly led by the US Air Force Space Command and the US Department of Transportation. Through the IFOR process, the team evaluated the current SSV requirement, proposed requirement modifications that can support current and emerging civil mission objectives, and assessed GPS program impacts.

To achieve the proposed requirement update, NASA performed a study to understand the current and emerging needs for civil users in the SSV, focusing on navigation mission drivers. It developed an updated SSV specification to support the needs of these current and emerging missions and it performed an extensive analysis of alternatives to explore non-GPS solutions. These were all key data products presented to and critiqued by the IFOR team. Through its work, NASA concluded that the GOES-R weather satellite series encompasses mission requirements that meet or exceed the needs of other emerging users. The proposed requirement contains GPS signal power, availability, and pseudorange accuracy necessary to meet the GOES-R navigation requirements specifically. Based on NASA's analysis, this level of performance is still significantly below that which GPS currently provides, but would ensure that emerging mission needs will be met by future GPS designs.

References 7 and 8 detail the derivation of the proposed requirement. The SSV user needs, proposed requirement and the current status of requirement implementation are summarized here.

Emerging SSV User Needs

An integral part of the GPS requirements development process is providing the evidence, through research and analysis, that there is a vital need for the proposed requirement to exist. For the SSV, NASA cited numerous space mission benefits and presented several spacecraft science and engineering applications that are operational, in development or being proposed for future operations in the SSV [7,8]. The GOES-R Earth weather satellite series was chosen by NASA to envelop the HEO/GEO SSV requirements because it has well-documented, validated requirements from which to compare and it is an operational spacecraft series with national and international importance. Its products, like GPS, are used in safety-of-life operations. It cannot meet its operational objectives without the GPS capabilities captured by NASA's proposed SSV requirement.

Below represents a summary of space user needs, including mission benefits and SSV mission types that were presented to the IFOR and support the need for the proposed GPS SSV requirement.

When compared to standard ranging methods, missions employing GNSS in the SSV derive the following benefits:

1. Benefit: Fast recovery from trajectory maneuvers; Improvement: From 5–10 hours to minutes.
2. Benefit: Improved operations cadence; Improvement: From standard ranging ops cadence (daily updates for GOES) to real-time cadence with reduced/no tracking, quicker response to anomalies, fewer shifts, less specialized training, lower software license costs.
3. Benefit: Increased satellite autonomy; Improvement: Savings of $500–750K per year; enables formation flying.
4. Benefit: Improved navigation performance including position, velocity, and navigation stability (or navigation jitter), for comparable sensing update rates; Improvement: Performance is mission and retrieval rate dependent. Examples include improvements from km-class to 1–10 meter-class positioning; navigation stability improved from not achievable, to 3–70 meters for rolling stability segments of 30 seconds to 30 minutes.
5. Benefit: Precise timing reducing the need for expensive on-board clocks; Improvement: Savings is mission dependent. For precise timing requirements, savings from $100'sK–1M, to $50K for OCXOs (Oven Controlled Crystal Oscillators) or $15K for VCXOs (Voltage Controlled Crystal Oscillators).

Figure 3 provides a summary of space mission applications that are enabled by precision GNSS navigation signals in the SSV. These include Earth remote sensing missions in GEO requiring precise geolocation, space weather satellite constellations, launch vehicles and spacecraft traveling away from Earth, formation flying and proximity operations missions, and others. Specific mission types, their benefits to humanity, and their SSV needs are described below.

Figure 3: SSV Space Mission Applications

Earth Weather

The textbook example of an Earth weather satellite with a critical need is the GOES-R series of spacecraft (GOES-R, S, T, U), shown in Figure 4. This spacecraft series is expected to provide transformative societal benefits by protecting people and property in the western hemisphere through improved weather prediction and operational early warnings of a significant number of diverse natural hazards, including tornados, flash floods, wildfires, etc. The societal benefits that are derived from the GOES-R series includes saving lives, protecting property and improved efficiency of national infrastructure, including routing of air traffic. Moreover, scientists expect that reliable extended forecasting will stretch from 3–5 days now to 5–7 days with GOES-R. Experts at the NWS and meteorological R&D universities such as the University of Wisconsin and Colorado State University view the GOES-R series to be a game-changer for weather prediction and natural disaster warning. [9, 10]

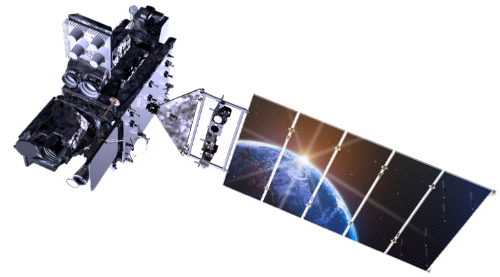
Figure 4: GOES-R Series Spacecraft

The improved data products from GOES-R, enabled through the IFOR recommended SSV specification, will also improve aviation safety, through more accurate prediction and communication of weather and natural hazards and it will cut aviation costs through optimal routing. Studies have shown cost benefits resulting from GOES-R to be at least $4.6 billion over the series lifecycle, from 2016–2035, in just four economic sectors: energy, aviation, irrigation agriculture and recreational boating. [11]

To achieve these benefits, the GOES-R series has several stringent navigation requirements, including in-track and cross-track position knowledge of 75 meters (3-sigma), navigation stability of 3 meters over 30 seconds and 35 meters over 900 seconds (3-sigma), and science outages less than 120 minutes per year [12]. The science outage requirement is 60 times better than the previous GOES series, significantly enhancing wind vector measurements which are crucial for severe storm tracking and prediction.

GOES-R cannot meet its science objectives with GPS capabilities at the level of the current GPS SSV specification. NASA's proposed updated requirement was formulated to just meet GOES-R's needs [8,12]. If the proposed requirement is not implemented, and GPS performance degrades to the current requirement level, GOES-R will not provide precise geolocation and wind velocity measurement products. The National Weather Service (NWS) will not utilize data products that cannot be trusted due to these losses of capability. The result will be that the new and enhanced data products from GOES-R would not be available to protect people and property in the western hemisphere. It should also be noted that NOAA has indicated that the European weather satellite system, EUMETSAT, and the Japanese weather satellite system are equally reliant on GPS in the SSV to support weather predictions in those regions of the globe. [13]

Space Weather

Space Weather and Heliophysics missions investigate the science and interaction of the Sun-Earth connection to deepen our understanding and, ultimately, the prediction of space weather. It includes the origin and evolution of the solar wind, low-energy cosmic rays, and the interaction of the Sun's heliosphere with the Earth's magnetic field and local interstellar medium. Space weather storms have the potential to render useless on-orbit spacecraft, on-orbit and ground-based electronics, wireless communications, GPS, electrical grids, etc. They also can impact the health of on-orbit astronauts through the exposure to ionizing radiation. The 1859 solar storm, the so-called "Carrington event," was so severe it impacted global telegraph operations. Clearly, space weather will impact civil and military users alike.

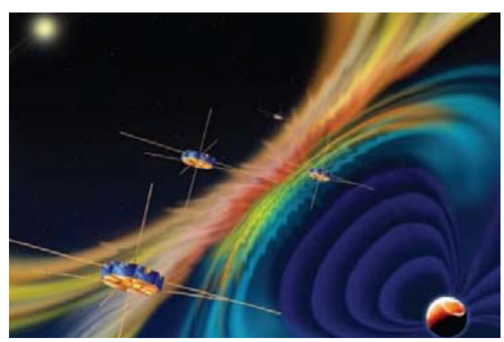
Figure 5: Four MMS Spacecraft Flying in Formation

Space Weather missions are enabling civil and military personnel to better understand, and ultimately predict, solar storms. Given the potential for severely impacting critical infrastructure, space weather events have the potential to be catastrophic from a cost and human

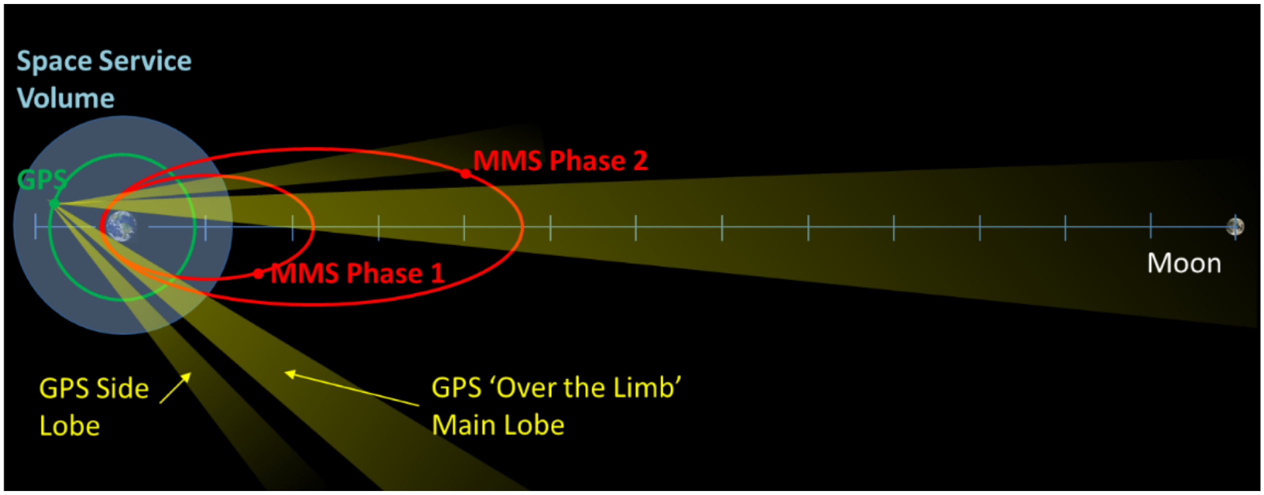

Figure 6: MMS Spacecraft Orbit in Cis-Lunar Space

impact perspective. In March 2015, the MMS mission [6] (Figure 5) was launched to better understand the underlying physics of space weather. MMS is a set of four spacecraft flying in formation performing observations of how the Sun and Earth's magnet field disconnects and reconnects. By measuring reconnections, MMS enables scientists to better predict this process, which is the final governor of space weather. MMS is in a highly eccentric high Earth orbit, with a Phase 1 mission orbit that spans 7,600 km by 76,000 km (Figure 6). The Phase 2 portion of the mission extends apogee to roughly 150,000 km. MMS relies on GPS in the HEO SSV for navigation and timing to enable onboard (autonomous) navigation and the fast cadence formation flying that would be impractical without GPS. Quick, autonomous recovery from trajectory maneuvers is critically important for MMS. Figure 7 [6] depicts the recovery performance of MMS to four perigee raising maneuvers with side lobes (in blue) and without side lobes (in red). This simulation of MMS vehicle performance shows that the side lobe signals significantly improve initial vehicle convergence, reduce peak errors at apogee and significantly improve maneuver recovery. Because MMS is a four-satellite formation flying mission, the expectation would be that mission operations would be complex, with substantial staffing required. However, mission costs are reduced and improved operations cadence becomes the norm through its GPS-enabled on-board navigation determination system. In fact, fewer operations shifts are required, and the team can more quickly respond to anomalies.

<u>Launch Vehicle Upper Stages and Missions Beyond the GEO Belt</u>

Launch vehicle upper stages employing GNSS will benefit commercial, civil government and military space users that use direct injection techniques to deploy their vehicles in HEO, GEO or beyond. High accuracy, high cadence position, velocity and time knowledge, afforded by GPS, is needed to improve insertion accuracy. This will reduce orbit correction delta-V's, allowing for increased mission mass or additional propellant margin. NASA's Space Launch System (SLS), is also considering employing GNSS in the SSV to improve upper stage disposal capabilities. This is needed due to the growth of trajectory errors from launch through to disposal. The disposal burn is particularly sensitive to this due to its occurrence late in the mission.

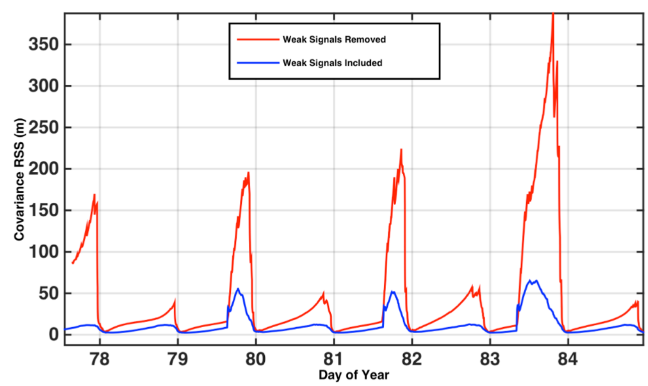

Figure 7: MMS Trajectory Corrections Employing GPS Aggregate Signal (blue) and with Side Lobes Removed (red)

Other potential benefits include reducing the need for highly accurate, state-of-the-art inertial measurement units (IMUs) for these missions, enabling cost savings and future mission evolutions paths, including autonomous pre-positioning of assets via autonomous rendezvous and docking to support future human spaceflight missions beyond LEO.

Satellite Servicing Missions

Satellite servicing, illustrated in Figure 8, will extend the life of spacecraft through upgrade, repair, refueling and orbit maintenance. It also can move errant or deactivated spacecraft to a safer disposal orbit. Satellite servicing was initially envisioned for use in spacecraft in GEO as this is where the highest density, highest cost satellite assets reside; however, vehicles or objects in other orbits will also benefit. Robotic servicers, using GNSS for PNT functions, will autonomously rendezvous & dock with a target spacecraft. The Servicer then performs necessary upgrades and repairs and places the target into its assigned, or new, orbit. Servicing concepts and detailed developments are underway by civil and military entities. Commercial satellite servicing is also being pursued. Satellite servicing has the potential of significantly reducing mission lifecycle costs or satellite replacement and launch costs. Critical on-orbit infrastructure could be easily repaired or refueled, eliminating long delays in mission continuity due to a spacecraft premature failures or long spacecraft development cycles.

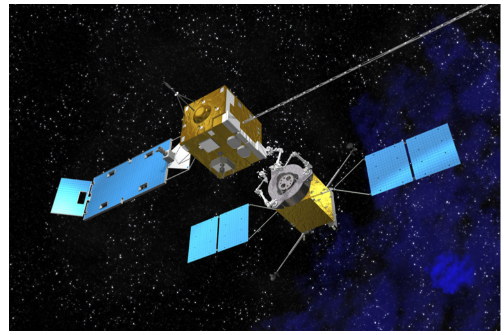

Figure 8: Example Satellite Servicing Mission

Formation Flying Missions

Formation flying, cluster flight, and autonomous constellation control represents an engineering technology tool that will open new mission, science and commercial opportunities through innovative, distributed data gathering techniques and through unique, innovative ways to perform science observations. Missions in this class span many different vehicle sizes, from CubeSats up to space station-class satellites. They also span a myriad of different objectives including Earth science, space science, telecommunications infrastructure, satellite servicing, human spaceflight, military and commercial endeavors. Employing extensive autonomous navigation and trajectory control systems, these missions can support missions such as debris collection, GEO Earth science formation flyers, GEO hosted payload formations, Sun occulters, gravity wave, exoplanet, dark energy, and x-ray science missions.

Narrowing GEO Belt Spacing

In space, the most coveted real estate is a GEO belt spot perched over the Earth's surface. Currently, the number of spacecraft in the GEO belt are limited by longitude spacing requirements that are in place to prevent spacecraft collisions and the resulting orbital debris. The primary limiting factor in tightening the GEO arc spacing is the spacecraft relative navigation errors from traditional ranging techniques, dispersion errors that occur after vehicle trajectory maneuvers and the slow operations cadence required to perform ground orbit determination using ranging techniques. GNSS at GEO enables closer satellite-to-satellite spacing, increasing the density of satellites in the GEO arc. This provides transformational benefits to commercial, civil space and military space users, supporting telecommunications, Earth and space weather, and military applications.

Summary

A rich, diverse set of SSV missions have been identified that employ the GPS aggregate signal to meet their mission objectives. Many of the space missions support the protection of global critical infrastructure and human lives. Since project managers will be reluctant to risk using this GPS utility without formal specification protections in place, there is significant motivation to ensure the SSV signals do not degrade beyond what is minimally acceptable for these missions.

Proposed GPS III SV11+ SSV Requirement

NASA took special care to design the proposed requirement to be minimal-impact to the GPS program. GOES-R needs were used to encompasses mission requirements that meet or exceed the needs of other emerging users. Only modest changes were made to the current GPS SSV requirement, and the structure was maintained. In particular, the proposed requirement was formulated based on a set of goals, including:

1. Capture the needs of GOES-R specifically, with no margin added
2. Specify system capability, not design
3. Do not drive an enhancement to the system over any previous design
4. Specify minimal changes to current requirement language
5. Require minimal additional verification effort

As with the existing SSV specification, the proposed requirement is a "triad" of three interrelated components: 1) Signal availability (% of time that 1 or 4 GPS signals are available; max outage time), 2) Minimum received signal power at GEO and 3) Maximum pseudorange accuracy (equivalent to user range error). Rather than changing existing specification values, the proposed requirement adds a second tier of capability specifically for HEO/GEO users. This second tier increases signal availability to nearly continuous for at least 1 signal and relaxes pseudorange accuracy from 0.8m RMS to 4m RMS as shown in Table 3. The minimum received power remains the same. Like the current requirement, this requirement augmentation applies to all signals (L1/L2/L5) and all codes.

Pseudorange accuracy (rms)	4m
1+ signal	≥ 99%
4+ signals	≥ 33%
Max outage	10 min

Table 3: Availability Requirement Augmentation

Recall that GOES-R performance was used to encompasses mission requirements that meet or exceed the needs of other emerging users.Figure 9 presents a comparison of the proposed aggregate signal availability for GOES-R. The main-lobe-only performance, equivalent to the capability required for GPS III SV 1–10, is shown in red. A conservative estimation of on-orbit performance capabilities (employing a 27-satellite constellation, minimum transmit power, worst-case side lobe power, etc.) is shown in green. NASA's proposed requirement for GOES-R is shown in blue; note the increase in availability over the current requirement, but the wide gap between what is proposed and what is actually available with the existing constellation.

In line with NASA's goals, this proposed requirement does not represent an enhancement to the system. In fact, if SV 11+ were to simply match the capability of the current lowest-performing design, then the requirement is expected to be fully met with significant margin. It does not mandate the current performance level—instead, it captures only the capability required by GOES-R and its follow-on spacecraft (S–U). It also does not mandate a particular design; while previous designs achieve performance beyond the proposed level via usage of the full aggregate signal, it is quite possible that a different pattern could

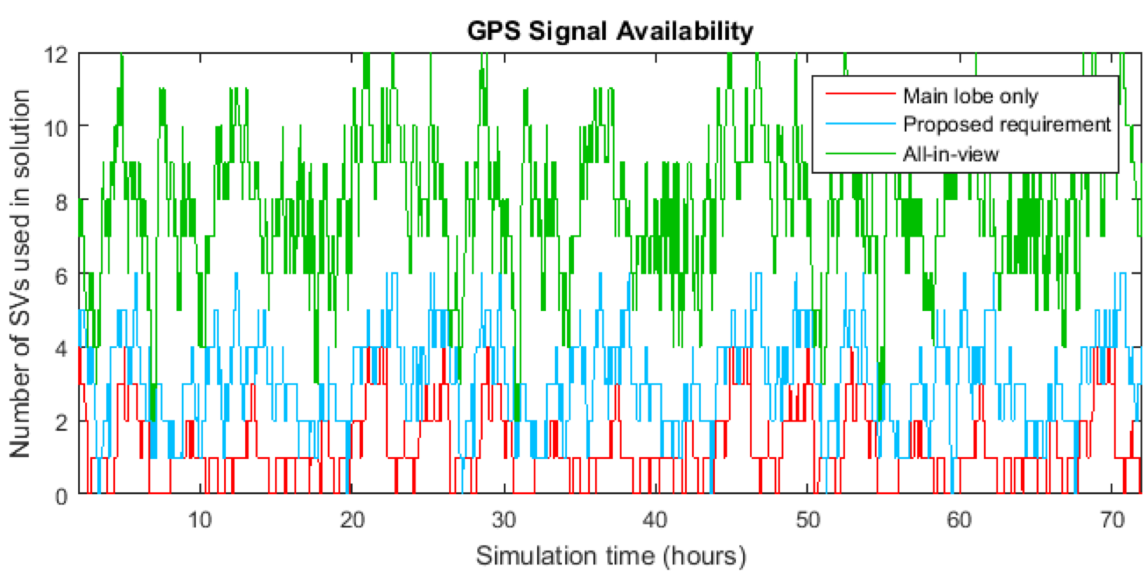

Figure 9: Proposed aggregate signal requirement performance (blue), compared to main lobe only performance (red) and current minimum performance capabilities with a 27satellite constellation (green), for a simulated GOES-R-like mission.

be used instead. All previous designs have differing patterns as well, especially in the side lobe regions, and all exceed the proposed capability with significant margin. Current flight data from missions such as MMS indicate that navigation nearly exclusively by tracking the GPS side lobe signals isn't only possible, but that it can result in 10m-class position knowledge. This performance is enabled by the approximately 3% total transmit power that exists in the sidelobes.

Requirement Adoption Status

The proposed updated SSV requirement shown here and documented in references 7 and 8 has been submitted to the IFOR for consideration for adoption for the upcoming GPS III SV11+ procurement received two external endorsements, one from NOAA, related to the GOES program, and one from a member of the USAF user community. All required documentation has been submitted to the IFOR in anticipation of a formal recommendation for adoption.

In late 2016, because of the larger set of potential user needs beyond the GOES-R series, the USAF established an Independent Strategic Assessment Group (ISAG) to perform a dedicated assessment and provide an independent recommendation on further specification of the SSV. The recommendation of the ISAG is expected in early 2017.

MOVING TOWARDS AN INTEROPERABLE GNSS SSV

The United Nations (UN) sponsored International Committee on GNSS (ICG) is leading the effort to coordinate the development of an interoperable SSV across the international PNT service providers. These providers include the U.S. GPS, China's BeiDou (or BDS), the European Galileo and the Russian GLONASS systems. It also includes the regional augmentation systems—NAVIC in India and QZSS in Japan. The vision of the ICG is "to encourage and facilitate compatibility, interoperability and transparency between all the satellite navigation systems, to promote and protect the use of their open service applications and thereby benefit the global community." SSV interoperability cannot be accomplished without PNT signal interoperability. Fortunately, the international community has made great strides; GNSS signal interoperability initiatives started in the early 2000s through bilateral discussions between the US government for GPS and Russia and Europe for GLONASS and Galileo respectively. When the ICG was formed in 2005, these discussions and agreements expanded to become multi-lateral across all constellation providers and regional augmentations. ICG Working Group-S, entitled "Global and Regional Navigation Satellite Systems, Signals and Services" coordinates GNSS signal interoperability. While still a work in progress, signal interoperability is becoming a reality. SSV coordination is accomplished as part of ICG Working Group B (WG-B): Enhancement of GNSS Performance, New Services and Capabilities.

To date, the global WG-B team has made significant progress in understanding the benefits of an interoperable GNSS SSV and performing the necessary pre-work, presentations, and analyses to move from a GPS-only specified SSV to a fully specified and interoperable SSV employing all GNSS signals in space. All WG-B participants believe that a fully interoperable GNSS SSV will result in significant benefits for future space users as it will allow for performance no single system can provide on its own. WG-B team members envision a future where a properly equipped user can access the signals from a combination of GNSS and regional constellations simultaneously to obtain improved performance and resiliency in the SSV through enhanced signal availability, diversity, and geometry.

Several WG-B initiatives are underway to better define the GNSS SSV capabilities and to predict the performance of a 100+ constellation of GNSS satellites that can be employed in the SSV. These initiatives include:

- **GNSS SSV Booklet**: Development of a publicly released booklet which describes the advantages of an interoperable GNSS SSV for space users; defines, in a template form, expected signal performance in the SSV (e.g. antenna beamwidth, signal strength, pseudorange error) for each GNSS constellation; and estimates the performance capabilities of an interoperable GNSS SSV
- **Definition/Assumption Maturation**: Developing standard definitions and ground rules and assumptions to perform unified, coordinated GNSS SSV analyses across the international team and to be employed for formal SSV specification
- **Joint SSV Analysis**: A three-phase joint analysis effort to characterize single-constellation and combined SSV performance within the SSV, using both a coverage grid approach, and a suite of example mission profiles. The results of this analysis will be captured in the GNSS SSV Booklet and in a set of coordinated conference and journal papers.
- **SSV Capabilities Outreach**: Coordination of a joint international outreach activity, targeted at space agencies, researchers, spacecraft mission designers, navigation engineers, GNSS providers, and others, to ensure that the capabilities and applicability of the interoperable GNSS SSV is understood.

- **Spaceborne GNSS Receivers**: Encouraging design and fabrication of multi-frequency, and multi-constellation GNSS receivers to exploit the SSV
- **Antenna / Electronics Characterization**: Encouraging the measurement of satellite transmit antenna patterns (pseudorange and phase vs. angle) pre-flight and designing spacecraft electronics with strict requirements on phase and group delay coherence
- **Guarantee of availability**: Encouraging adoption of guarantees of SSV capabilities (e.g. via specification) by each constellation provider through future constellation design changes

The WG-B team meets twice per year face-to-face, in June and November, and monthly by teleconference, to move the above initiatives towards completion. Good progress has been made across all constellations and augmentations. For example, active SSV initiatives are underway in the US, through the IFOR process, and in Europe, through a European Commission SSV study. At the most recent ICG, Russia released information on operational missions they are conducting in the SSV. While still in development, China is capturing lessons learned and ideas to garner maximum use of the SSV via BDS. The GNSS SSV Booklet is expected to be completed by mid-2017, after the WG-B internationally coordinated SSV analysis is complete. In accord with the above initiatives, at the most recent, November 2016, ICG meeting, the WG-B formally recommended the following:

1. Service Providers, supported by Space Agencies and Research Institutions, are encouraged to define the necessary steps and to implement them in order to support SSV in future generations of satellites. Service Providers and Space Agencies are invited to report back to WG-B on their progress on a regular basis.

2. In order to fully support in-depth mission-specific navigation studies, WG-B invites the providers to consider for the future, to provide the following additional data if available:
   - GNSS transmit antenna gain patterns for each frequency, measured by antenna panel elevation angle at multiple azimuth cuts, at least to the extent provided in each constellation's SSV template.
   - In the long term, also consider providing GNSS transmit antenna phase center and group delay patterns for each frequency

WG-B Internationally Coordinated SSV Analysis

In conjunction with its activities in defining, standardizing, and publicizing the multi-GNSS interoperable SSV, WG-B is leading a multinational analysis effort to simulate and document the individual and combined capabilities of each constellation for space users. This effort is being coordinated through the development of analysis ground rules and assumptions that are agreed upon by WG-B team members. Each national team performs the planned analyses independently, and the results are then compared to provide a measure of independent verification. Ultimately, the goal is for each national team to develop the capability to simulate SSV capabilities for all constellations, to a minimum level of fidelity. This capability can then be used as a foundation for future internationally-coordinated analyses. This effort will also enable the international WG-B team to more accurately determine the benefits and sensitivities in using the collective GNSS constellations and augmentations as a combined SSV navigation capability.

The WG-B analysis effort consists of three phases, starting with a simple geometric analysis and increasing complexity and fidelity at each step (Figure 10). Phase 1 is a geometrical coverage analysis of GNSS signal visibility at GEO altitude. This was completed in May 2016 and the results were presented at the ICG-11 WG-B meetings in November 2016 in Sochi, Russia. Phase 2 is a GNSS signal-based analysis, using the same coverage-based methods, but applying a link budget calculation to determine visibility. This phase includes simple antenna patterns of each GNSS constellation/augmentation coupled with the power output of each system, as provided by each constellation manufacturer, to represent the expected SSV signals for each constellation/augmentation system. A representative weak signal GNSS receiver was placed on spacecraft in pre-planned areas of the GEO belt and an RF analysis was performed to determine signal availability statistics at each location and for each GNSS constellation element. This study was completed in September 2016 and was presented at the ICG-11 WG-B meetings in November 2016 in Sochi, Russia. Phase 3 will extend this analysis to specific user mission scenarios, including those in GEO, highly elliptical orbits extending beyond GEO, and a mission on a trans-Lunar trajectory. Phase 3 represents a full end-to-end analysis of a set of mission scenarios that represent real SSV missions currently underway or that are planned for the future. The Phase 3 analysis is planned to begin in early January 2017, with analysis completion planned for March 2017. Once completed, these end-to-end tools will facilitate more in-depth analyses of SSV mission scenarios. By developing and validating the analysis tools across national teams, WG-B will ensure that the results across all constellation and augmentation teams will be consistent and comparable.

Phase 1 Analysis

As shown in Figure 10, the WG-B Phase 1 analysis [14] was designed as a simple geometric visibility analysis based on a coverage grid, shown in Figure 11, placed at the limit of the SSV (36,000 km). Two major classes of metrics were simulated: average percent of time across the grid in which 1 or more, or 4 or more, satellites are visible simultaneously; and the maximum signal outage time for any grid point. Each constellation was propagated from a standardized set of Keplerian elements for a total of 14 days, and at each timestep, visibility was calculated between each constellation and each point in the coverage grid. If the point fell inside the signal coverage cone of any single satellite, it was considered visible. The constellation propagations were performed using a simple two-body force model with a low fidelity rotation-only Earth model. The grid was defined as having a 5 deg spacing at the equator, but such that each point covers equal area, increasing angular spacing at the poles. This method was chosen to avoid overweighting of points at the poles. Since each constellation provider provided different data for the L1 and L5 frequencies, the analysis was performed on both cases.

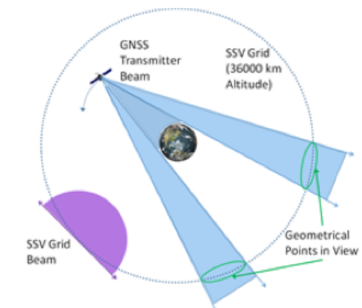

Figure 10: Phase 1 analysis geometry

The results of this analysis for the L1 frequency are shown in Table 4. The single-satellite visibility varies from a low value of 27% for the QZSS constellation, which is expected because of its geographic focus, to over 97% for the BDS constellation, which has a geostationary component. The values of 90% for GPS is consistent with the existing GPS SSV specification, though different data and methods were used in the derivation. The four-or-more visibility results show a more compelling scenario, in which visibility improves from a low of nearly 0% visibiltity for the MEO-only systems, to over 94% visibility when all systems are combined. The maximum outage results show similar improvements. In this case, the NAVIC results are not applicable, since that system does not use the L1 frequency. "(SD)" indicates that the maximum outage across the coverage grid was the entire scenario duration (i.e. at least one grid point never received the indicated coverage).

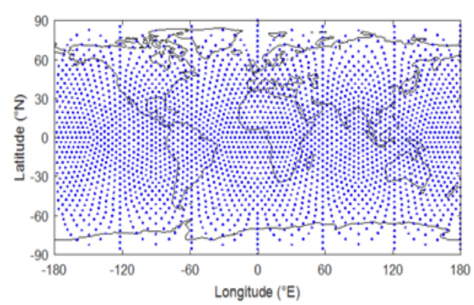

Figure 11: Phase 1 coverage grid

Table 4: Phase 1 Analysis Results - L1

L1	BDS	Galileo	GLONASS	GPS	QZSS	All
1+ Availability	97%	78%	59%	90%	26%	**99%**
4+ Availability	24%	1%	0%	4%	0%	**94%**
Max 1+ Outage	45 min	98 min	134 min	111 min	(SD)	**39 min**
Max 4+ Outage	(SD)	(SD)	(SD)	(SD)	(SD)	**97 min**

Phase 2 Analysis

For the Phase 2 analysis, illustrated in Figure 12, two major sources of fidelity were added:

- Addition of a link budget calculation to determine signal visibility, instead of a simple geometric metric
- Addition of an actual receiver at each grid point, with a C/N0 tracking threshold

While still a simplified analysis, the Phase 2 effort was intended to increase the capability of each team's simulation tools to eventually support a full Phase 3 simulation. Four C/N0 tracking thresholds were ultimately modeled: 15 dBHz, 20 dBHz, 25 dBHz, and 30 dBHz. This adds some credence to the results, as it shows the capability of a user receiver to actually utilize the type of performance indicated in the Phase 1 results.

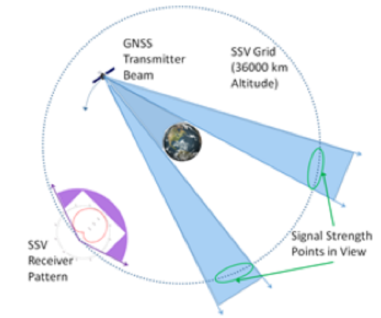

Figure 12: Phase 2 analysis geometry

The results of the Phase 2 simulation for the L1 frequency are shown in Table 5. Note that only the 15 dBHz and 20 dBHz cases are shown, as higher tracking thresholds were determined to be insufficient to provide significant visibility at GEO. These results show a similar trend as in Phase 1: very low four-or-more visibility for each individual constellation, but a relatively high value when the constellations are combined. For the 20 dBHz case, this metric drops from 94% in the geometric analysis to 62%, indicating that much of the signal is below the tracking threshold when the full link budget is considered. The difference is primarily due to a drop in BDS visibility, likely due to the extra path loss from the BDS GEO satellites.

Table 5: Phase 2 analysis results

	BDS	**Galileo**	**GLONASS**	**GPS**	**QZSS**	**All**
20 dBHz						
1+ Availability	69%	78%	0%	90%	0%	**99%**
Max 1+ Outage	70	98	(SD)	111	(SD)	**49 min**
4+ Availability	0%	1%	0%	4%	0%	**62%**
Max 4+ Outage	(SD)	(SD)	(SD)	(SD)	(SD)	**223 min**
15 dBHz						
1+ Availability	97%	78%	59%	90%	26%	**99%**
Max 1+ Outage	45	98	134	111	(SD)	**39 min**
4+ Availability	24%	1%	0%	4%	0%	**94%**
Max 4+ Outage	(SD)	(SD)	(SD)	(SD)	(SD)	**97 min**

Phase 3 Analysis

Phase 3, currently underway, represents the most specific, and also the most realistic, set of analyses. Instead of applying a coverage grid approach, three individual missions, Figure 13, were chosen to illustrate real-world capabilities:

- GEO spacecraft at six latitude locations
- Highly-elliptical mission extending well beyond the SSV, similar to NASA's MMS and ESA's PROBA-3
- Lunar transfer mission, similar to NASA's Exploration Mission 1 concept

For each mission, a realistic receiver antenna or antennas will be modeled, either as a patch or a high-gain design. One common gain pattern for each type was chosen for the analysis. In addition, the antenna orientation,

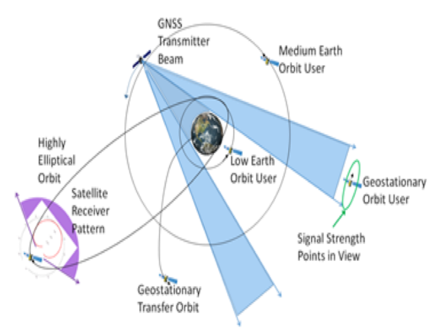

Figure 13: Phase 3 analysis geometry

spacecraft attitude, and a common receiver tracking threshold of 20 dBHz will be modeled for each example mission. Two of the three, the HEO and lunar mission, feature both nadir-pointing and zenith-pointing receive antennas. The chosen architectures are illustrated in Figure 15.

The results of Phase 3 will include the number of individual and combined GNSS signals visible over time for each mission type, and also as a function of altitude. These will serve not only as an example for the SSV capabilities for these types of missions, but also as a guide for the general visibility characteristics throughout and beyond the SSV. Phase 3 is planned for completion by April 2017.

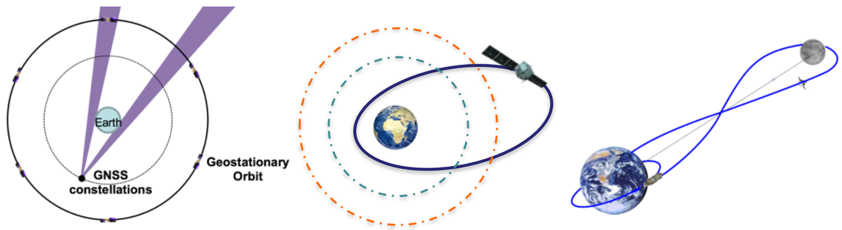

Figure 14: (a) GEO mission definition, (b) HEO mission definition, (c) lunar mission definition

WG-B Analysis Conclusions and Forward Plan

When complete, the WG-B joint analysis will definitively demonstrate the primary benefit of the interoperable multi-GNSS SSV: near-continuous availability of GNSS signals up to (and beyond) GEO altitude. Looking specifically at the Phase 2 results, at a 15 dBHz tracking threshold, the availability of four simultaneous signals increases from a maximum of 24% (for BDS), to a combined total of 94% using all available constellations. Phase 3 will extend these general metrics to real-world mission scenarios. It is anticipated that the Phase 3 analysis will be completed in early 2017, leading to a release of the completed GNSS SSV Booklet during the spring. The detailed technical analysis will be captured separately in a series of joint analysis papers, to be presented to the international space user community through conferences and technical journals. At the completion of the analysis effort, all providers will have a baseline capability to perform SSV capability analysis internally using internationally-agreed assumptions and constellation data. This capability will enable more detailed individual or joint analyses in the future as the interoperable GNSS SSV continues to develop.

Interoperability and SSV Initiatives in Europe

Europe has a multi-pronged effort to exploit GNSS in the SSV. Since the late 1990's they have sponsored several SSV characterization flight experiments [15, 16, 17, 18]. European space agencies have several missions in development, including the PROBA-3 technology mission and the EUMETSAT weather satellite. They are coordinating the development of several multi-GNSS SSV receivers, including the Astrium LION, the RUAG PODRIX and the Surrey SGR-GEO. And the European Commission recently initiated an 18 month SSV study to support the next generation build of Galileo.

A premier upcoming ESA technology validation mission that plans to employ GNSS in the SSV is the Project for On-Board Autonomy-3 (PROBA-3) mission (figure 16). PROBA-3 is a high altitude solar occultation mission using precise formation flying in a 600 by 60,000 km orbit to perform detailed observations of the Sun's corona. The primary objectives of Solar occultation missions, or solar chronographs, are to enable scientists to perform detailed measurements of the Sun's corona.The Sun's corona is currently not well observed due to the fact that it is about a million times dimmer that the Sun. It can only be observed if an object the size of the Sun's disk, is placed in front of the sun to occult the significantly brighter Sun's surface. In the past, this could only be accomplished during Solar total eclipses. On PROBA-3, this will be accomplished using GNSS and other sensors to fly two spacecraft in a precise,

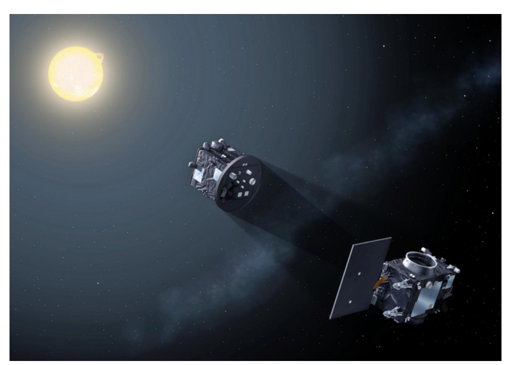

Figure 15: PROBA-3 Solar Occultation Mission

choreographed formation, with one spacecraft, a coronagraph, taking measurements and a second, a spherical shield, which serves to occult the Sun. Internationally, this solar science has great interest and could not be done without the use of GNSS in the SSV.

CONCLUSIONS

Many emerging space missions are poised to benefit from improved PNT solutions through the employment of GNSS signals in the Space Service Volume (SSV)—the volume of space starting at 3000 km above the Earth and extending to geostationary altitudes. Currently, several operational missions use either GPS or GLONASS signals in the SSV to improve their vehicle navigation performance. These missions derive additional benefits from GNSS in the SSV, including fast trajectory maneuver recovery, reduced need for expensive on-board clocks and increased space vehicle autonomy, lowering mission operations costs and enabling formation flying. Several initiatives are being conducted in the United States and internationally to ensure that GNSS signals in the SSV are available, robust, and yield precise navigation performance. These initiatives include a NASA-led requirements enhancement effort to ensure continued GPS SSV signal robustness as future constellation designs are deployed, and the United Nations-sponsored International Committee on GNSS (ICG) effort to coordinate SSV development across all international GNSS constellations and regional augmentations.

Missions using GPS in the SSV currently take advantage of aggregate (main and sidelobe) signal reception to boost their navigation and timing performance. Use of sidelobe signals, in concert with the mainlobe signal, improves overall signal availability and signal geometry for missions in the HEO and GEO regime. However, these missions are vulnerable to GPS constellation design changes because the performance enabled by the aggregate signal is not fully specified. NASA is utilizing the government's IFOR process to develop an updated SSV requirement which will capture a portion of the improved SSV signal availability that already exists on-orbit, to the level that is needed by emerging stakeholder users. To achieve the proposed requirement update, NASA performed a study to understand civil space user needs, developed the updated SSV requirement language, and performed an extensive analysis of alternatives to explore non-GPS solutions. NASA's proposed requirement augments the current SSV specification with a second tier of capability specifically for HEO/GEO users, increasing signal availability to nearly continuous for 1 signal in view and relaxing pseudorange accuracy from 0.8m RMS to 4m RMS. This proposed requirement is significantly below the level of performance that GPS currently provides but would ensure that emerging mission needs will be met by future GPS designs. It is NASA's contention that this proposed requirement is minimal-impact and represents the lowest-cost solution for current and future PNT needs in the SSV. Since project managers will be reluctant to risk using GPS without formal specification protections in place, there is significant motivation to implement this proposed requirement as it will ensure the SSV signals do not degrade beyond what is minimally acceptable for current and emerging missions.

In addition to the NASA-led GPS requirements initiative, great strides have been made internationally in the coordination of interoperable signals and specifications that enable future space missions to employ the full complement of GNSS signals from all constellations and augmentations. The UN-sponsored ICG is encouraging PNT service providers to develop an interoperable multi-GNSS SSV via common definitions, constellation performance characterization and SSV specification for future constellation developments. Additionally, the ICG WG-B team is leading a multinational three-phase SSV analysis effort to simulate and document the individual and combined capabilities of each constellation for space users. With two of 3 phases of this effort complete, results show substantial availability improvements when all GNSS constellations are employed. Single satellite availability is 99% when all GNSS constellations employed versus ~90% for GPS only, and four satellite availability jumps from a few percent with GPS to 62% availability with all GNSS signals employed. In addition to the enhanced signal availability, an interoperable multi-GNSS SSV will result in a more resilient PNT system for space users, providing enhanced robustness to degradations of any one system, whether intentional, due to jamming or spoofing denial of service attacks, or unintentional due to constellation spacecraft or ground system issues.

Humanity is poised to reap great benefits resulting from the expansion and use of GNSS in the SSV. As has been demonstrated in other user segments, order-of-magnitude returns on investment to national governments are possible, and extraordinary societal benefits are anticipated through protection of lives and property by missions in the SSV. However, this potential must be supported by commitments to continue to support and develop the SSV: for GPS, the current SSV specification must adequately protect future use enabled currently by the aggregate signal; and for GNSS, the capabilities that are emerging now must be characterized and protected for the future via individual constellation specifications. Only then will an interoperable multi-GNSS SSV move from dream to reality.

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ACRONYMS

AoA – Analysis of Alternatives
AT&T – American Telephone & Telegraph
BDS – BeiDou Satellite Constellation
ESA – European Space Agency
GEO – Geostationary Earth Orbit
GN&C – Guidance, Navigation & Control
GNSS – Global Navigation Satellite System
GOES – Geostationary Operational Environmental Satellite
GRC – Glenn Research Center
GSFC – Goddard Space Flight Center
GPS – Global Positioning System
HEO – High Earth Orbit

ICG – International Committee on GNSS
IFOR – Interagency Forum for Operational Requirements
IMU – Inertial Measurement Unit
ION – Institute of Navigation
LEO – Low Earth Orbit
MEO – Medium Earth Orbit
MMS – Magnetospheric Multiscale Spacecraft
NASA – National Aeronautics and Space Administration
NWS – National Weather Service
NAVIC – Navigation Indian Constellation
NOAA – National Oceanic and Atmospheric Administration
OCXO – Oven Controlled Crystal Oscillator
ORD – Operational Requirements Document
PNT – Positioning, Navigation and Timing
PROBA-3 – Project for On-Board Autonomy-3
PVT – Position, Velocity, and Timing
QZSS – Quasi-Zenith Satellite System
RF – Radio Frequency
RMS – Root Mean Squared
SLS – Space Launch System
SSV – Space Service Volume
SV – Satellite Vehicle
TSV – Terrestrial Service Volume
UN – United Nations
URE – User Range Error
VCXO – Voltage Controlled Crystal Oscillators
V&V – Verification & Validation
WG-B – ICG Working Group-B